Estimating the Costs, Benefits, and Return on Investment of Integrated Semiconductor Process Metrology

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Executive Summary

Cost of ownership (COO) was developed to address the economic and productive performance of a fabrication tool by estimating the total life-cycle cost of a specific semiconductor process step. But COO for equipment required to support manufacturing such as metrology tools is also needed. With a few modifications, COO can be applied to integrated metrology systems as well[1]. COO analysis for integrated metrology is more complex than for fabrication equipment, requiring a two part analysis. First, the costs of operating the tool with and without metrology are estimated. Second, the cost impact of metrology on the processes being measured must be estimated. The benefits of integrated metrology are estimated by considering the impact of metrology on a process or product. When characterization information improves the process, metrology adds value to the process.

Overview of Cost of Ownership

SEMI E35 defines COO as the full cost of embedding, operating, and decommissioning, in a factory and laboratory environment, a system needed to accommodate a required volume[2]. The significant COO inputs include:

- Equipment cost
- Operating cost
- Yield
- Down time
- Throughput rate
- Value of completed unit
- Cost of discarding a good unit
- Cost of shipping a bad unit

These factors are combined in the COO equation[3]:

$$COO = \frac{CF + CR + CY}{L \times TPT \times Y \times U} \tag{1}$$

where:

COO = Cost per good unit
CF = Fixed Cost
CR = Recurring Cost
CY = Cost of Yield Loss

L = Equipment Life
TPT = Throughput Rate
Y = Yield
U = Utilization

Fixed costs are incurred once during the life of the system and are associated with the acquisition and installation of equipment. Fixed costs include costs such as equipment purchase, installation and setup, facility modifications, initial training, and initial calibration costs. Recurring costs are incurred on an accrued basis. Recurring costs such as material, labor, repair, standards, calibration, utility and overhead expenses are costs that are incurred during equipment operation. Cost of yield loss is the value of scrap caused by the process step. Process scrap identified at the step of interest but caused by prior processing is part of the prior process tool COO. Thus, yield losses caused by the processing tool must be clearly separated from prior losses. The sum of these costs forms the numerator of the COO equation.

The denominator of equation [1] is an estimate of the number of good units produced during the life of the system. Throughput rate is based on measurement and handling times such as sample preparation, loading and unloading, reporting, and other overhead operation. It excludes training, repair, and calibration times since these are included in utilization. Yield may be defined as the ratio of good units compared to the total number of units produced, including rework. Utilization is the ratio of actual usage compared to total available time. Utilization includes repair and maintenance time, both scheduled and unscheduled; setup and calibration time; and standby time. It shows the impact of non-productive time on cost and normalizes ideal throughput to a realistic estimate. Utilization is estimated using SEMI E10 definitions for availability, reliability and maintainability[4].

For metrology, COO may be described in terms of cost per measurement. For a 100% sample, cost per device equals cost per measurement, but for less than 100% samples, the cost per device is some fraction of the cost per measurement.

Impacts of Metrology on the Process

Since the process and metrology are in series, process throughput depends on metrology methods. Further, since the process requires measurement, there is an impact of measurement on WIP (Work In Process) (See Table I). WIP inventory between a process step and subsequent inspection is at risk if the process drifts. Several operating methods minimize that risk. Send ahead (or look ahead) samples* eliminate WIP risk but reduce process throughput and utilization. Integrated in-situ metrology operation minimizes risk with very little impact on utilization.

Table I. Sample Plan Impact on Process[5]

Sample Plan	Throughput	Utilization	α/β Risk
100%	High	Low	Low
1 of N	Low	Low	High
N per day	Low	Low	High
N per event	Low	Low	High
Send ahead	High	High	Low
In-situ	Low	Low	Low

* A send-ahead sample requires one or more wafers be processed, then submitted for measurement. The remaining wafers in the lot wait until the results of the measurement are complete and the equipment is adjusted. Only then will the remaining wafers in the lot be processed.

Since product or process yield at subsequent steps depends on the accuracy of metrology, we must consider the costs of discarding a good device and the cost of accepting a bad device. Measurement risk is illustrated in Table II[6]. Minimizing the cost of shipping a bad device is one purpose of metrology. However, if the sampling plan or methods are insufficient, bad devices will be shipped. But if specifications are too restrictive, then good devices may be rejected. Guard banding specifications increases α probability in order to decrease β probability.

Table II. Measurement Risk

True State	Measured Result	Error
Good	Good	None
Bad	Bad	None
Good	Bad	Type I (α)
Bad	Good	Type II (β)

The cost of discarding a good device is estimated by:

$$C_\alpha = \alpha \times WIP \times V_p \tag{2}$$

where:

C_α = Cost of discarding good device
α = Probability of discarding good device
V_p = Value of device at metrology
WIP = Work in process

and the cost of shipping a bad device may be estimated by:

$$C_\beta = \beta \times WIP \times V_c \tag{3}$$

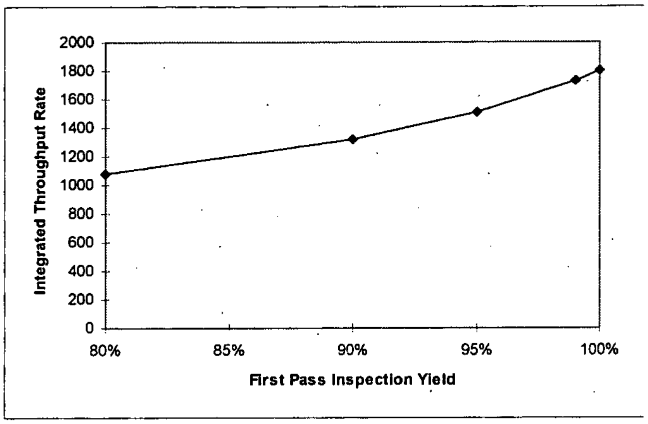
where:

C_β = Cost of shipping bad device
β = Probability of shipping bad device
V_c = Value of replacement device
WIP = Work in process

The probabilities of discarding a good device and of shipping a bad device are related to the variance of the measurement. These probabilities may be reduced by reducing variance, increasing sample size, or developing more robust processes.

Impacts of Integration

Comparing integrated inspection strategies with nonintegrated methods allows the user to determine the costs and benefits of manufacturing integration. One impact of integration is the impact on throughput rate. Throughput rate is another important COO driver. Lower inspection yields will have a greater impact on throughput rate than higher yields as shown in the following example based on device assembly analysis[7].



Assembly Throughput Rate vs. Inspection Yield

Return on Investment Analysis

The two part COO for metrology analysis allows comparing the benefits of metrology with the metrology COO to estimate the return on investment (ROI) in metrology. Most of the costs of metrology are captured by the basic COO equation. These costs are expressed in terms of cost per measurement. The benefits of metrology are estimated by considering the impact of metrology on a process or product. The knowledge gained by characterizing a process or product leads to the following benefits:

- Reduced cost of shipping bad device
- Reduced cost of rejecting good device
- Improved sample methods
- Improved process throughput
- Reduced impact of mis-measurement on WIP

Return on metrology investment may be described by the following simple equations:

$$ROI = \frac{B_{Product} + B_{Process}}{MetrologyCOO} \tag{4}$$

Knowledge gained through metrology adds value to the process or product through continuous learning and improvement. Thus if characterization information improves the process, then metrology is a value added step.

In-Situ Particle Measurement Example[8]

The prevention and reduction of contamination are critical steps to the improvement of manufacturing productivity. Contamination-related scrap losses result in lost equipment productivity and increased wafer cost. Contamination increases COO by:

- Increasing maintenance and downtime
- Increasing equipment costs
- Increasing scrap loss

Standard measurement and control methods to monitor in-process particle contamination include particle count monitors and test wafers. These impact the productivity of manufacturing equipment. Running particle monitoring wafers may use about 5% of daily production time, more than 8 hours per week of lost production. Table III illustrates the difference between in-situ and external particle monitoring methods in terms of cost per wafer.

Table III. Particle Monitoring Impact on COO

	External Measurement	In Situ Measurement
Tool and Metrology Equipment Cost	$1,000,000	$1,000,000
Tool Throughput	15 wafers/hour	15 wafers/hour
Productivity Impact	5%	0%
OEE*	86.8%	91.0%
COO	$4.57	$4.38
Depreciation	$1.27	$1.21
Maintenance	$1.02	$0.98
Floor Space Costs	$0.84	$0.80
Labor	$0.82	$0.79

In this example we estimated the impact of metrology by comparing the COO of the process step with external metrology and with in situ metrology. We assumed that the total cost of the process tool and the metrology systems were the same in both cases. We also assumed that yield loss and maintenance downtime were the same. These very conservative assumptions still result in a COO that is 4% lower with in situ metrology†.

Cost of Ownership Model for Epitaxial Silicon Fabrication with Integrated Wafer State Metrology

This section describes a calculation of the cost and benefits of integrated film thickness monitoring for the epitaxial silicon process. The calculation details the potential impact of installing the On-Line Technologies ***Epi On-Line***™ integrated FTIR film thickness monitoring system on the Applied Materials Epi Centura HT 200 mm single wafer epitaxial silicon CVD cluster tool. We calculate both the cost impact of installing the film thickness monitor on the cluster tool and the impact to the cost of the process itself in terms of yield costs, test wafer consumption, increased utilization, etc.

The analysis showed that one key factor in evaluating the benefit of the tool involves whether the tool in question is a bottleneck tool. If the tool is a bottleneck to the overall manufacturing process, i.e. if demand exceeds capacity for the process, then even modest increases in tool utilization translate into significant gains in cost of ownership and profitability. Further gains are provided by reduced recurring costs involving monitor wafers, yield losses and consumables. If the tool is not a bottleneck, i.e. the tool sits idle waiting for incoming product and work orders much of the time, then increases in wafer per hour throughput result in increased idle time, and the benefits of increased production capacity are not fully realized. The savings in this case come primarily from reduced consumables, labor, and yield costs.

The assumptions and results in the cost of ownership model are summarized in Table IV for the case of a bottleneck tool. We have (conservatively) assumed that the integrated metrology will be installed as an

* Overall Equipment Effectiveness

† TWO COOL® data files for all examples in this paper are available upon request from WWK. Request "Integrated Measurement Examples " by email to support@wwk.com.

augmentation to existing metrology and that no savings are to be had by eliminating the capital costs of the metrology processes already in place within a factory. The savings are gained through reduction of test wafers used to tune up thickness, reductions in routine monitor wafers, higher equipment utilization through reduced waiting times for metrology and a higher proportion of product wafers to test wafers. 100% real-time monitoring of epitaxial thickness will improve yield by identifying and classifying out-of range process chambers more quickly, before more wafers are misprocessed and scrapped. The particular numbers presented represent typical values for the commodity p/p+ epitaxial silicon industry, and were obtained from discussions with several silicon suppliers. Estimates of reduced monitor wafer usage, reduced labor, yield loss and other benefits were obtained through analysis of the beta site operations at Wacker Siltronic.

Table IV. Conservative COO estimate for a bottleneck epitaxial silicon CVD tool comparing current production methods, with production augmented by integrated epitaxial thickness metrology.

	Standalone	Integrated	Savings
COO (cost per good epi wafer)	$18.58	$17.42	$1.16
Product wafers per month per tool	15,257	15,823	566
Cost of Sales per Month	$1,351,486	$1,383,219	$31,733
Gross Revenue per month	$1,525,672	$1,582,254	$56,581
Gross Profit per month per cluster tool	$174,186	$199,035	$24,849
Installation Cost for integrated metrology	$0	$100,000	
Payback time for integrated metrology technology installation (months) Capital cost relative to gross profit method	4.0		
Wafer Selling Price	**100**	100	
Epi price premium over epi substrate	**30**	30	
Average Monitor wafer price (mostly reclaims)	**40**	40	
Tool Throughput (W/H)	**27**	27	
Tool Life (Y)	**5**	5	
Fixed Cost	$5,200,000	$5,300,000	$100,000
Cost of Yield Loss (Scrap)	$4,817,912	$4,734,303	-$83,610
Monitor wafer costs	$1,132,458	$774,981	-$357,476
Recurring Costs (excluding monitor wafer costs)	$5,010,000	$4,943,600	-$66,400
Scrapped wafers	45,770	45,094	-676
Utilization - OEE	77.41%	80.28%	
Yield	**95.00%**	**95.25%**	
Test Wafer percentage	**3.00%**	**2.00%**	
Downtime Sheduled	**2.00%**	**2.00%**	
Downtime Unscheduled	**4.00%**	**3.00%**	
Waiting for metrology	**4.00%**	**3.00%**	
Setup	**2.00%**	**2.00%**	
Idle	**4%**	**4%**	

Table V shows a similar calculation for which the tool is assumed to operate at chronic under-capacity. In this mode of operation, the orders received or some other external factor determine the level of production, and small changes in tool throughput translate into small variations in tool idle times. Improvements in tool productivity that translate into financial benefit then are those that impact consumables such as monitor wafers and chemicals, or recurring costs such as labor.

Table V. Conservative COO estimate for a non-bottleneck epitaxial silicon CVD tool comparing current production methods, with production augmented by integrated epitaxial thickness metrology.

	Standalone	Integrated	Savings
COO (cost per good epi wafer)	$15.01	$14.32	$0.69
Product wafers per month per tool	**15000**	15000	0
Cost of Sales per Month	$1,275,167	$1,264,753	-$10,413
Gross Revenue per month	$1,500,000	$1,500,000	$0
Gross Profit per month per cluster tool	$224,833	$235,247	$10,413
Installation Cost for integrated metrology	$0	$100,000	
Payback time for integrated metrology technology installation (months) Capital cost relative to gross profit method	9.6		
Wafer Selling Price	**100**	100	
Epi price premium over epi substrate	**30**	30	
Average Monitor wafer price (mostly reclaims)	**40**	40	
Tool Throughput (W/H)	**30**	30	
Tool Life (Y)	**5**	5	
Fixed Cost	$5,200,000	$5,300,000	$100,000
Cost of Yield Loss (Scrap)	$1,800,000	$1,710,000	-$90,000
Monitor wafer costs	$1,500,000	$1,017,995	-$482,005
Recurring Costs (excluding monitor wafer costs)	$5,010,000	$4,857,200	-$152,800
Scrapped wafers	45,000	42,750	-2,250
Utilization - OEE	68.49%	68.49%	
Yield	**95.00%**	**95.25%**	
Test Wafer Percentage	**4.00%**	**2.75%**	
Downtime Sheduled	**2.00%**	**2.00%**	
Downtime Unscheduled	**4.00%**	**3.00%**	
Waiting for metrology	**4.00%**	**3.00%**	
Setup	**2.00%**	**2.00%**	
Idle	**13%**	**16%**	

Discussion

The calculations shown in Tables IV and V show that substantial potential savings are to be had via the introduction of integrated film thickness metrology, but the magnitude of the savings depends greatly on the details of the operation. Though the SEMATECH specification for cost of ownership does not address the issue of bottlenecking, the most significant potential gains in productivity hinges on whether or not the tool is operated in bottleneck mode. In a well planned facility, any given tool is likely to bottleneck production at some time or another, but the exact percentage of time in which this situation occurs depends on many factors that are difficult to control (including an unpredictably fluctuating demand for wafers). In circumstances when capacity exceeds demand, there may be substantial benefits to shutting down a tool for extended periods, this may put the remaining tools in a near bottleneck state, depending on the instantaneous demand and the cost to recommission a tool that has been shut down for extended periods. Labor reduction and test wafer elimination were also found to be significant drivers for integrated metrology. Monitor wafer usage and labor practices tend to be very fab dependent, and to properly estimate these parameters, close interaction with the fab management is required.

Payback times were calculated in terms of profit generated by the process vs. the additional fixed cost to install the integrated measurement system. For a tool operating as the production bottleneck, the estimated payback time to install the integrated measurement system was 4.0 months. For a tool operating at significant under capacity, the payback time expanded to 9.6 months.

In addition to a reduced COO, the use of integrated metrology has also proven to be capable of yielding better product quality through "on-the-fly" tunability of the manufacturing equipment. Improved epitaxial thickness matching of multiple chambers on the cluster tool as well as enhanced uniformity tuning have been achieved.

References

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